A Modified Shear Interface Design Method for Precast Concrete Deck Panels

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Abstract

Shear connectors are critical components in composite bridge systems, particularly in precast concrete deck panels, where they enable load transfer across the interface and ensure structural integrity. The current AASHTO LRFD design provisions rely primarily on shear-friction theory, which considers only the friction component explicitly and assumes shear reinforcement yields during loading. However, this assumption is often inaccurate for precast systems, where shear connectors typically lack sufficient embedment length to develop full yield stress. Additionally, cohesion and dowel action are either oversimplified or completely neglected. This paper proposes a refined shear interface design method that incorporates three contributing mechanisms: cohesion, friction, and dowel action. A closed-form equation is introduced for each component, including a new expression for dowel action based on plastic hinge formation in embedded reinforcement. The model accounts for both material properties and geometric detailing of connectors. To validate the proposed method, two comprehensive databases of experimental push-off tests were assembled. The first includes large-diameter shear connectors (≥ #6) with high-strength steel, and the second comprises smaller connectors with conventional yield stress. Comparative analysis shows that the proposed model predicts interface shear capacity more accurately than the AASHTO LRFD method, especially for larger connectors. For the first database, the proposed method improved prediction accuracy by 20–25%, while remaining consistent with AASHTO for smaller connectors. This research provides a more reliable framework for shear design in precast deck panel systems, with the potential to improve safety margins and optimize reinforcement detailing in accelerated bridge construction applications.

Keywords
Shear connectors; Interface shear; Precast deck panels; Dowel action; Composite bridges

1. Introduction
Precast concrete deck panels are widely used in modern bridge construction, particularly in projects that prioritize accelerated construction, quality control, and long-term durability. A critical aspect of their performance lies in the shear transfer across the interface between the precast panels and the supporting girders. This interface shear transfer enables composite action and ensures structural integrity under service and ultimate loads.

The most widely adopted framework for interface shear design is the shear-friction theory, which is incorporated into several major design codes, including AASHTO LRFD, ACI 318, and the fib Model Code. The theory was originally introduced to predict the behavior of new-to-old concrete interfaces and is based on the premise that relative slippage at the joint leads to cracking, inducing tension in the reinforcement crossing the interface. As these bars yield, the resulting clamping force generates shear resistance through friction. While this model has provided a practical foundation for decades, its assumptions are not always applicable in precast systems.

In precast deck panel applications, shear connectors often have limited embedment lengths, which may prevent them from reaching yield stress. Furthermore, current code provisions generally neglect the effects of cohesion and dowel action, which can both significantly influence shear capacity. As a result, existing design methods may be overly conservative or inconsistent in predicting interface performance in precast systems.

This paper proposes a refined interface shear design method that explicitly incorporates the contributions of cohesion, friction, and dowel action. A closed-form equation is developed, and the method is evaluated using a broad range of published experimental data. The goal is to provide a more accurate and rational framework for designing shear connectors in precast deck systems used in bridge construction.

2. Theory and Proposed Method

Interface shear transfer in composite concrete systems has traditionally been modeled using the shear-friction theory, which was originally proposed by Birkeland and Birkeland (1966) to predict the behavior of joints between new and old concrete. This approach is now embedded in major design standards, including AASHTO LRFD (2020), ACI 318 (2021), and the fib Model Code (2010), and is commonly used for corbels, precast decks, and steel–concrete composite systems.

The underlying concept is that, as slip occurs along the interface, cracks form and widen, inducing tension in the reinforcement crossing the plane. As the reinforcement yields, it applies a clamping force that enables frictional resistance to develop along the crack. While this model has proven effective in many applications, it overlooks two important mechanisms, cohesion and dowel action, and may be unconservative in precast deck systems, where connectors often lack sufficient embedment to fully develop yield stress.

This section presents a refined model that integrates all three mechanisms, cohesion, friction, and dowel action, into a closed-form expression for interface shear capacity. The general form of the proposed equation is:

$$V_{ni} = V_{ci} + V_{fi} + V_{di} \qquad \text{(Eq. 1)}$$

Where:

V_{ni} : Total interface shear capacity
V_{ci} : Contribution from cohesion
V_{fi} : Contribution from friction
V_{di} : Contribution from dowel action

2.1 Cohesion

Cohesion refers to the bond strength present before significant cracking occurs and is particularly relevant in roughened or monolithic concrete joints. It includes both chemical adhesion and aggregate interlock. AASHTO LRFD includes cohesion in some interface configurations using a simplified term:

$$V_{ci} = c.A_{cv} \qquad \text{(Eq. 2)}$$

Where:

c: cohesion factor (typically 0.28 MPa or 40 psi for intentionally roughened surfaces)
A_{cv} : concrete interface area

While some codes omit cohesion entirely, Walraven and Reinhardt (1981) and Mattock et al. (1976) demonstrated that cohesion can provide meaningful resistance in early loading stages.

2.2 Friction

Friction is generated after cracking occurs and is governed by the clamping force across the interface. In the classic shear-friction model, this force results from the yield strength of the reinforcement and any external compressive load normal to the interface. However, in many precast systems, reinforcement may not reach yield due to insufficient development length. Therefore, the proposed method considers the actual tensile stress in the bar, f_s , and calculates friction as:

$$V_{fi} = \mu\ (A_s f_s + P_c) \qquad \text{(Eq. 3)}$$

Where:

μ: friction coefficient (typically 1.0–1.4 for roughened surfaces)
A_s : area of reinforcement crossing the interface
f_s : tensile stress in the steel (not exceeding 60 ksi per AASHTO recommendations)
P_c : any permanent axial compressive force

This approach aligns with the findings of Mattock and Hawkins (1972), who observed that friction resistance depends strongly on bar stress and surface condition, not just on full yielding.

2.3 Dowel Action

Dowel action occurs when reinforcing bars crossing the interface resist lateral displacement through bending. As shear develops, the bar deforms laterally and forms plastic hinges at either side of the joint, especially in systems with end anchorage or headed bars. The lateral resistance is referred to as dowel stiffness, and its ultimate contribution can be approximated as (Hatami, 2014):

$$V_{di} = k.\ n.\ f_d.\ d_b^3 / (3.5\ l_a) \qquad \text{(Eq. 4)}$$

Where:

- n: number of connectors
- d_b : bar diameter
- l_a : embedment length in the pocket or panel
- f_d : dowel stress = $f_y - f_s$
- f_y : yield strength of steel
- k: factor for bar type (e.g., 2 for headed bars)

Experimental work by Loov and Patnaik (1994) and Kahn and Mitchell (2002) demonstrated that dowel action contributes significantly to shear resistance, particularly in large-diameter bars embedded in confined concrete.

2.4 Conceptual Overview

Fig. 1 illustrates the shear connector and interface region in a typical precast deck panel system. It is assumed that the connector will develop plastic hinges on both sides of the pocket, contributing to dowel action. Unlike traditional methods, the proposed model treats these mechanisms as additive, recognizing that cohesion, friction, and dowel action can all be active to varying degrees depending on detailing and load level.

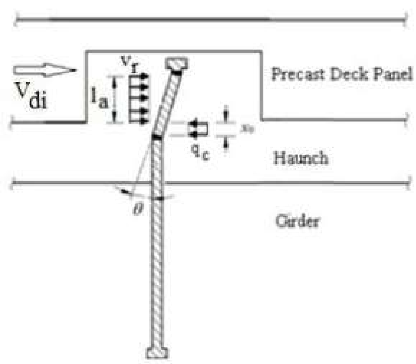

Fig. 1: Plastic hinges in shear connectors

3. Experimental Data and Validation

To evaluate the accuracy and reliability of the proposed shear interface model, two distinct experimental databases were assembled using published push-off test results. These databases capture a wide range of shear connector sizes, concrete strengths, and reinforcement properties that are commonly encountered in precast deck systems.

3. 1 Database 1: Large-Diameter Shear Connectors

The first database includes 28 push-off test specimens featuring large-diameter connectors (bar size ≥ #6) and high-strength steel reinforcement (yield stress > 60 ksi). This data set was compiled from studies by Valluvan (1999), Mekulasi (2002), Girgis and Tadros (2007), and Henely (2009), all of which investigated precast deck systems and composite bridge elements.

The concrete compressive strength for these specimens ranged from 1.8 ksi to 7.0 ksi. For each test, the interface shear capacity was calculated using both the AASHTO LRFD equation and the proposed method. The results were compared in terms of the Ultimate shear force per connector (Fig. 2), the Ultimate shear stress per connector (Fig. 3), and the Ratio of experimental to predicted values (Fig. 4).

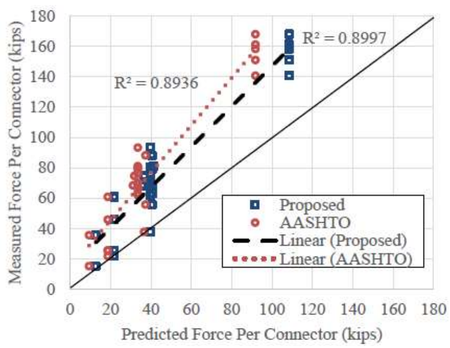

Fig. 2: Predicted shear force per connector (bar size ≥ #6)

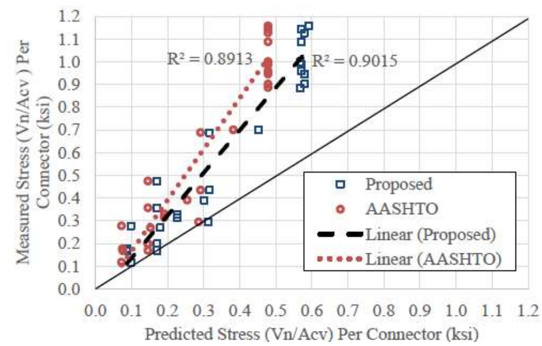

Fig. 3: Predicted shear stress per connector (bar size ≥ #6)

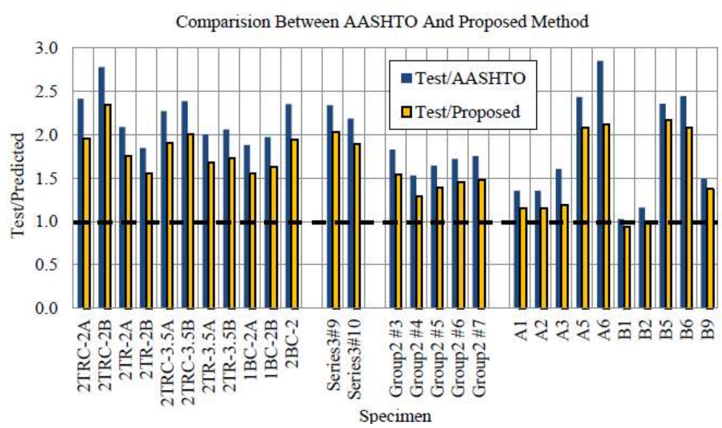

Fig. 4: Comparison between the proposed method and the AASHTO LRFD (bar size ≥ #6)

The results show that the proposed method provides a more accurate prediction of shear capacity for large connectors, with an average improvement of 20–25% over the AASHTO LRFD predictions. This improvement is largely attributed to the inclusion of dowel action and more realistic modeling of friction based on tensile stress rather than assumed yielding.

3. 2 Database 2: Regular Shear Connectors

The second database contains 260 push-off test results from earlier studies involving standard-size reinforcement (bar size < #6) and conventional yield strength (≤ 60 ksi). This set draws from experimental work conducted over several decades, including: Saemann and Washa (1964), Hofbeck et al. (1969), Mattock et al. (1975, 1976), Walraven and Reinhardt (1981), Bass et al. (1989), Loov and Patnaik (1994), Choi (1996), Kahn and Mitchell (2002), Kahn and Slapkus (2004), Issa et al. (2006), Scott (2010), and Harries et al. (2012).

The concrete compressive strengths in these tests ranged from 1.5 ksi to 12.8 ksi. Because these studies primarily focused on cast-in-place conditions or lightly reinforced interfaces, they provide a benchmark for evaluating the consistency of the proposed method with current code-based predictions.

The results for ultimate shear force per connector, ultimate shear stress per connector, and test-to-predicted ratios are shown in Fig. 5, Fig.6, and Fig. 7, respectively.

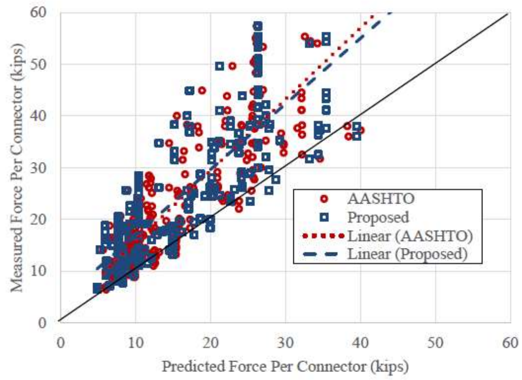

Fig. 5: Predicted shear force per connector (bar size < #6)

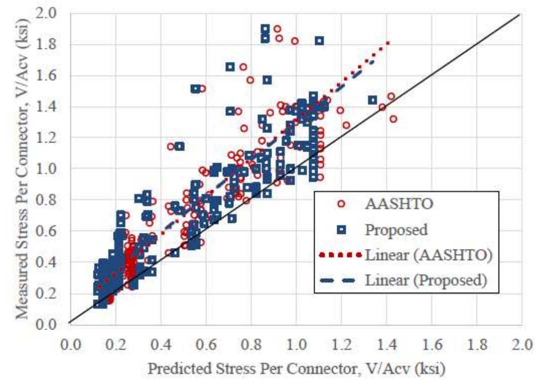

Fig. 6: Predicted shear stress per connector (bar size < #6)

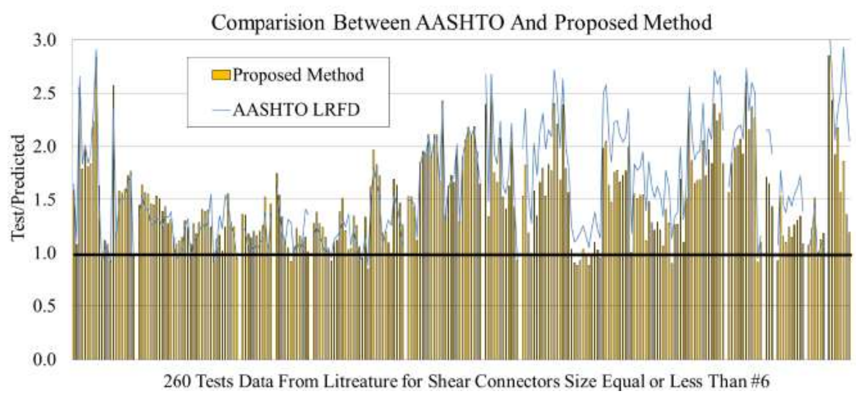

Fig. 7: Comparison between the proposed method and the AASHTO LRFD for shear connectors equal to or less than #6

Both the proposed method and AASHTO LRFD yielded similar results for these smaller connectors. This indicates that the proposed method remains consistent with current design assumptions for conventional applications and does not introduce unnecessary complexity where dowel action is less significant.

3.3 Summary of Validation Results

The validation results demonstrate that the proposed model improves the prediction of shear capacity in precast systems with large-diameter connectors, while maintaining consistency with established code predictions for smaller, cast-in-place applications. The improved performance is attributed to the explicit inclusion of dowel action and a more rational treatment of the frictional contribution based on actual bar stress. This dual database approach supports the use of the proposed model in both research and practice and highlights the importance of connector geometry and detailing when applying simplified shear-friction theory.

4. Upper Limit Criteria and Design Implications

As the amount of transverse reinforcement or the interface clamping force increases, the predicted shear capacity of a joint also increases. However, there is a practical limit to this behavior. Beyond a certain point, the governing failure mode can shift from slip at the interface to crushing of the concrete along the joint. This transition introduces a physical upper bound on the interface shear resistance that must be accounted for in any rational design method.

4.1 Review of Code-Based Upper Limits

Several design codes have established upper bounds on shear friction capacity to prevent concrete crushing at the interface. For instance, AASHTO LRFD (2020) specifies a maximum interface shear stress of:

$$V_{ni} \leq min\ (0.25\ f_c',\ 1500\ psi) \qquad \text{(Eq. 5)}$$

This limit applies to connections between precast deck panels and monolithically cast concrete, especially when the interface is intentionally roughened. ACI 318 (2019) and the fib Model Code (2010) adopt similar limits, typically in the range of $0.25\, f_c^{'}$ to $0.33\, f_c^{'}$, depending on interface roughness and construction type.

While these values are based on extensive laboratory testing, they are generally conservative and often do not account for the mechanical contribution of reinforcement beyond friction. In systems using large-diameter connectors or high-strength materials, especially in precast applications, the potential for higher shear capacity exists but must be evaluated cautiously.

4.2 Proposed Upper Limit for the New Method

To identify a rational upper limit for the proposed model, a focused analysis was conducted using experimental data from Valluvan (1999), Mekulasi (2002), and Girgis and Tadros (2007). These studies involved high-strength concrete, large-diameter reinforcement, and realistic precast interface conditions.

Test results were plotted against predicted interface shear capacity (Fig. 8), revealing substantial scatter at the upper end of the data. Despite the variation, a clear trend emerged: increasing reinforcement or clamping force beyond a certain point does not always result in proportionally higher capacity, particularly when localized crushing becomes dominant. Based on this trend, a conservative upper limit of $0.25\, f_c^{'}$ is recommended for the frictional component, consistent with AASHTO LRFD. This limit aligns with the 95% confidence envelope for the dataset and provides a balance between safety and design flexibility.

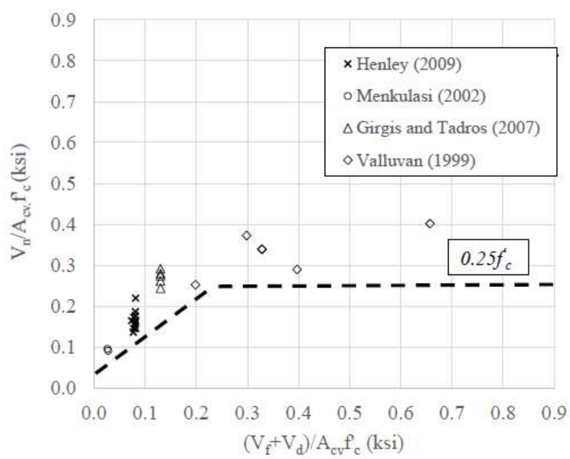

Fig. 8: Proposed method and results from the literature for interface shear capacity

In addition, an upper limit is proposed for the dowel action component, based on the plastic moment capacity of the embedded bar. Following principles outlined by Mattock et al. (1975), the maximum dowel force is estimated as:

$$V_{di,max} = A_s f_y / \sqrt{3} \qquad (6)$$

This expression assumes plastic hinge formation on both sides of the connector and limits the dowel contribution to a physically realizable mechanism within the surrounding concrete.

4.3 Design Implications

The proposed upper bounds provide practical guidance for engineers implementing the new model. In particular: i) for precast deck panel systems, where large-diameter connectors and partial embedment are common, the refined model offers more accurate capacity estimates than the current AASHTO LRFD provisions, which assume full yielding regardless of connector detailing, ii) the inclusion of dowel action allows the designer to account for additional resistance that is physically present in most precast systems, especially when reinforcement is properly anchored and permitted to bend across the joint, and iii) the proposed limits also serve as safeguards to prevent unconservative designs in cases of high axial clamping or excessive reinforcement, where localized failure modes may govern.

By incorporating these upper limits, the refined method maintains consistency with established safety margins while improving prediction accuracy and better reflecting the actual mechanics of interface shear transfer in precast systems.

5. Conclusions

This paper introduced a refined method for designing shear connectors in precast concrete deck panel systems by incorporating the combined effects of cohesion, friction, and dowel action. Unlike conventional approaches such as AASHTO LRFD, which primarily rely on shear-friction theory and assume yielding of reinforcement, the proposed method provides a more realistic representation of interface behavior, particularly in precast systems where limited embedment length often prevents full development of yield stress. The proposed model was validated using two experimental databases compiled from the published literature. The first focused on large-diameter shear connectors with high-strength steel, and the second included smaller, more conventional connectors. The model demonstrated improved prediction accuracy, particularly for larger connectors, where the inclusion of dowel action and adjusted frictional behavior significantly reduced the conservatism found in existing code provisions. For standard connectors, the model remained consistent with current design assumptions, offering a seamless transition for broader adoption. Upper limit criteria were also established to ensure that the model remains bound by physical failure mechanisms such as concrete crushing and plastic hinge formation. These criteria align with existing code recommendations but are better tailored to precast applications, offering a safer and more efficient framework for performance-based design. Although this paper focused on literature-based validation, additional experimental testing and finite element modeling conducted by the lead author provide further support for the method. These extended studies will be included in future publications. The model presented here contributes to the ongoing development of more rational and structurally representative approaches to shear connector design in precast bridge systems.

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